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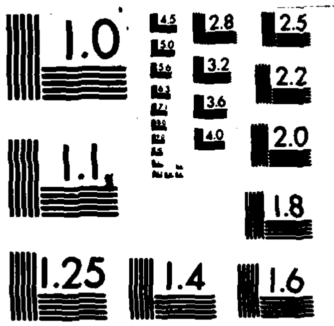

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This ~~is the final report for a long-term ARO~~ research project designed to evaluate the effects of air pollutants on forests in southwestern Virginia. Extensive field studies utilizing tree coring techniques and open-top chamber experiments have shown that air pollutants from RAAP have periodically caused foliar injury to air pollution-sensitive trees and suppressed forest growth. Laboratory studies showed the genetic basis for interspecific differences in air pollution sensitivity and showed pollutants generally caused reductions (OVER)

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20. Abstract (continued)

in transpiration and photosynthesis. Field and laboratory studies carried out between 1974 and 1980 are reviewed in this report.

More recent studies have documented patterns of ozone dispersion through the ridge-valley Appalachian Mountains. Higher elevation sites tended to have higher ozone concentrations. Rainfall chemistry has also been characterized for a station in southwestern Virginia.

A rainfall simulator has been designed and built in order to reproduce rainfall in controlled laboratory experiments. This simulator provides natural-sized raindrops, distributes droplets evenly over a surface, and is chemically inert. Studies on defining the role of rainfall chemistry and ozone impact on plants are now underway.

Recent experimental work has shown white ash to be susceptible to ambient air pollutants in southwestern Virginia. Susceptibility was defined by both foliar injury and growth suppression. These studies complement analysis already made on the air pollution sensitivity of coniferous species which grow near RAAP.

RAINFALL CHEMISTRY AND POTENTIAL BENEFICIAL/DETRIMENTAL IMPACT TO INDIGENOUS VEGETATION

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A. STATEMENT OF THE PROBLEM

The Army Research Office (ARO) has supported studies on the effects of gaseous air pollutants and acidic precipitation on vegetation native to southwestern Virginia since the early 1970's. ARO interest in these studies stems from concerns that air pollutants from a munitions plant located in Radford, Virginia reduced growth rates for trees in the local area. This cause and effect relationship between air pollution and tree growth was established by Dr. John Skelly and his associates at Virginia Polytechnic Institute and State University. Studies by Dr. Skelly and his colleagues showed periods of high munitions productivity were associated with periods of low tree growth rates. Additional research has identified a range of tree and understory species which are sensitive to ambient pollution levels as well as characterized air quality and rainfall chemistry at several sites in southwestern Virginia.

This is the final (termination) report for all ARO-sponsored air pollution impact research funded at the Laboratory for Air Pollution Impact to Agriculture and Forestry (LAPIAF). The purposes of this report are to:

1. Summarize the major findings of all air pollution impact studies funded by ARO by staff associated with the LAPIAF.
2. Present monitoring data describing air quality and acid rain chemistry obtained for sites in southwestern Virginia.
3. Introduce the design of a rainfall simulator which was developed to apply artificial, but realistic, rainfall on plants in the laboratory.
4. Describe the results of various air pollution treatments on foliar injury and the growth of green and white ash seedlings.

1. SUMMARY OF PREVIOUS STUDIES

a. Field Studies

The U.S. Radford Army Ammunition Plant, located six kilometers north of Radford, Virginia, is one of the largest industrial complexes in southwestern Virginia. The production of nitrogenous based ammunitions has led to the emission of various air pollutants, primary of which is oxides of nitrogen with nitrogen dioxide being the most biologically important constituent. The RAAP produces its own electricity and steam through coal-fired generators which emit significant quantities of sulfur dioxide. Ozone is also known to exist in the ambient air at the RAAP. Thus, three of the major phytotoxic air pollutants (O_3, SO_2, and NO_x) are present to varying degrees in the ambient atmosphere at this facility. Because RAAP is situated in a forested geographic bowl and isolated from other major air pollution sources, it is an exceptional area for determining the growth impact of air pollution on forest trees and also offers an excellent location to field test a bioindicator system.

Eastern white pine was chosen as a major indicator species for studying pollution abatement at RAAP after consideration of the following facts: 1) the species is indigenous to the area and found abundantly within the installation; 2) the species has been shown in previous studies to exhibit the strongest correlation between average annual increment growth and RAAP production rates; 3) this species has shown great variation in air pollution sensitivity on a clonal basis, but individual trees have responded with a high degree of uniformity, and 4) this species can be clonally propagated to insure uniform genetic characteristics.

Previous work at the RAAP by Skelly, Moore and Stone (1972), Stone and Skelly (1974), and Phillips, Skelly and Burkhart (1977a, b) have presented the history of this point source for NO_x and SO_2 and its usefulness for forest tree growth studies.

Skelly, Moore and Stone (1972) conducted height growth studies in a 13-year-old stand of white pine at the RAAP. Asymptomatic trees as well as chlorotic dwarf trees were observed; severely affected trees (excluding the chlorotic dwarfs) averaged 66% of the height of asymptomatic trees. Previously, Stone and Skelly (1974) also extensively studied the annual radial increment growth in a mixed white pine stand and in a yellow poplar (*Liriodendron tulipifera* L.) stand. They used simple linear regression analysis to evaluate the relationship of annual radial increment growth to annual production levels (an indicator of air pollution levels). A significant ($p = 0.01$) inverse relationship between growth and air pollution was demonstrated in both white pine and yellow poplar and their results were the basis for continued studies.

Phillips, Skelly and Burkhart (1977a, b) extended these types of observations into three loblolly pine stands and used multiple linear regression analyses with annual radial increment growth as the dependent variable and annual production levels, total annual rainfall, annual seasonal rainfall and age to evaluate pollution impact to that species. Once again, a significant ($p = 0.01$) inverse relationship was demonstrated in two of three stands examined with regard to growth and previous production history at RAAP. The third stand was sufficiently depressed in growth due to its proximal location to the Oleum Plant so that growth differences could not be defined, ie. a constant source of pollution impact. Phillips, Skelly and Burkhart (1977b) also re-evaluated the white pine stand studied by Stone and Skelly (1974) in an effort to identify growth reduction in trees of differing symptom - pollutant sensitivity classes. Four levels of symptom expression were used to categorize the sample trees for computer analysis of their respective growth rates in response to their previous exposure to SO_2 and NO_x. Analysis using regression correlations revealed no significant growth rate differences between symptom classes and production peaks, ie. the growth of asymptomatic trees was reduced as much as trees with symptoms during the time of sampling.

Later work reported by Nicholson and Skelly (1977) indicated that growth in this white pine stand has continued to increase since 1972 as a result of reduced levels of production and concurrent efforts in pollution abatement of the major sources of SO_2 and NO_x with RAAP. Nicholson also used selected white pines from this same group as ortets for the propagation of clonal lines of differing sensitivities to O_3, SO_2 and NO_2. Grafts were made using 2:0 rootstock and scion from 12 ortets of white pine growing at RAAP; the 12 ortets represented four symptom severity classes (three ortets/class) ranging from trees with greater than 25% of their crowns exhibiting necrotic tipburn to those with healthy crowns. Five ramets/clone were used in each six-hour treatment of 1) O_3-10 pphm; 2) O_3-30 pphm; 3) NO_2-10 pphm; 4) NO_2-30 pphm; 5) O_3-10 + NO_2-10 pphm; 6) O_3-10 + NO_2-30 pphm; 7) control. All ramets were returned to a charcoal-filtered greenhouse immediately after treatment. The ramets were evaluated prior to fumigation and then 2, 7 and 14 days thereafter for visible symptoms. Analysis of variance showed that there were significant differences at the 5% level between clones, classes and treatments. After 14 days, three of the 12 clones tested showed the effects of an O_3-NO_2 synergism in treatment 5; while seven clones showed the same reaction in treatment 6.

Variation in pollution sensitivity within loblolly pine and American sycamore has also been examined (Kress and Skelly, 1976; Kress, 1976). Eighteen full-sib families of loblolly pine and 14 half-sib families of sycamore were screened for sensitivity to O_3, SO_2 or NO_2. Sensitive and tolerant families of loblolly pine were identified, and are currently being utilized in other indoor and field studies. There were strong indications of genetic variability in American sycamore also.

The studies by Kress (1977) and Kress and Skelly (1977) have examined the height growth of loblolly pine and American sycamore exposed to long-term low-levels of O_3, SO_2 and/or NO_2. Seedlings of a sensitive and tolerant family were exposed to 5 pphm O_3, 14 pphm SO_2, and 10 pphm NO_2 (singly and in combination) six hours per day for 28 consecutive days.

Significant growth reductions were noted in the sensitive loblolly pine family exposed to O_3 alone and SO_2 alone. The O_3 + SO_2-exposed sensitive plants were significantly smaller than the O_3 alone-treated plants, and the O_3 + SO_2 + NO_2-exposed plants were significantly smaller than the O_3 + SO_2-treated plants. With the tolerant loblolly pine family, there was no significant response to O_3 alone or SO_2 alone. The O_3 + SO_2-exposed plants were significantly smaller than the O_3 alone-exposed plants, but there was no added effect with the addition of NO_2. The tolerant loblolly pine family was always taller than the sensitive family, and the difference was significant in most of the pollution treatments. Foliar injury was never greater than 5%. The sensitive half-sib family of American sycamore exhibited significant growth reduction when exposed to O_3. The O_3 + SO_2-exposed plants were significantly smaller than the O_3 fumigated plants, and the O_3 + SO_2 + NO_2-exposed plants were significantly smaller than the O_3 + SO_2-exposed plants. The tolerant family exhibited significant growth reductions only in the combination treatments. The O_3 + SO_2-treated plants were significantly smaller than the control or O_3-treated plants, and the O_3 + SO_2 + NO_2-exposed plants were significantly smaller than the O_3 + SO_2-exposed plants. Overall, the sensitive family suffered greater height reductions, 45% versus 34% for the tolerant family. In none of the pollution treatments were foliar symptoms evident on American sycamore. The pollutant concentrations used in these studies were below the NAAQS for each pollutant, and were also below the levels that have been monitored at RAAP in the past.

Another study currently in progress is utilizing the sensitive and tolerant families of loblolly pine planted in open-top chambers at RAAP. Data from the 1977 growing season showed that the sensitive family suffered a 30% and 39% height growth reduction growing at two separate sites when filtered air was compared with non-filtered air. The tolerant family at the same two sites exhibited a 3% increase and a 28% decrease in height growth, respectively.

b. Laboratory Studies

Laboratory fumigation studies were initiated in order to study the responses of eastern white pine to air pollution during controlled exposures. The trees were raised from cuttings obtained near the RAAP. The cuttings were collected from trees which appeared to range widely in air pollution sensitivity and were grafted to root stocks of commercially-raised trees. Of these cuttings, eight were selected and propagated in a greenhouse following grafting on to root stock, a period of dormancy, and bud break. The specific goals of the experiments were to determine if foliar sensitivity of cuttings was affected by root stocks, to associate air pollution sensitivity with morphological characteristics of the foliage, and to determine if there are differences in the physiological responses of cuttings that are either resistant or tolerant to air pollution.

The eight clones were collected from trees representing three air pollution sensitivity groups (sensitive, intermediate and tolerant). Cloned material which grew following propagation retained respective rankings of air pollution tolerance following laboratory fumigations (Yang et al., 1982). Needle length did not correlate with air pollution sensitivity whereas dry needle weight appeared to be a better indicator of air pollution tolerance. Thus, plant morphology could not be used to predict air pollution tolerance of eastern white pine. Nontheless, air pollution tolerance was shown to be genetically controlled and to range widely within this species.

Net photosynthesis, dark respiration, and transpiration were measured for two-year-old cloned cuttings of eastern white pine (Yang et al., 1983a, b). The plants were fumigated with ozone in the CSTR chambers while enclosed in vessels in order to monitor CO_2 and H_2O exchange between the whole cutting and air. A 4-h exposure to 0.1, 0.2 and 0.3 $\mu L\ L^{-1}$ reduced photosynthesis for clones in all three air pollution sensitivity groups. Transpiration declined for all plants except clones of intermediate sensitivity. The sensitive clone was the slowest to recover after the ozone was removed. Respiration was stimulated for the sensitive clone. Thus, air pollution sensitivity for this clone may reflect 1) reduced ability to recover normal metabolic rates in ozone-free air and 2) ozone-caused stimulation in respiration.

In summary, numerous studies have been conducted and shown that the Radford Army Ammunition Plant was a source of SO_2 and NO_2 that has had an impact on surrounding forest vegetation. Our studies have clearly identified this impact on various facets of tree growth and physiology.

2. DESCRIPTION OF RAIN CHEMISTRY AND AIR QUALITY IN SOUTHWESTERN VIRGINIA

Ambient levels of ozone are known to reduce plant growth throughout the eastern United States, including southwestern Virginia. In addition, acidity in rainfall found throughout much of this area has been implicated in acidifying fresh waters and soils, as well as reducing the vigor and growth rates of vegetation. Air quality and rainfall chemistry were monitored at several sites in western Virginia in order to characterize trends of air pollution dispersal. Analysis of air quality at these sites provides a picture of background levels of air pollution in the area near the Radford munitions factory and is important in defining the extent to which this factory contributes to the air pollution burden in this area.

a. Monitoring Sites, Methods, and Procedures

i) Monitoring gaseous pollutants. Ozone is a gaseous air pollutant and, during the summer months, is the air pollutant which poses the most serious threat to agriculture and forestry in Virginia. Ozone was continuously monitored at four stations in the western part of the state (Fig. 1) which were located to represent a range of elevations. Two sites were located at Big Meadows in Shenandoah National Park and at Rocky Knob near Floyd, Virginia. These sites are at 1050 m elevation and 950 m elevation, respectively, and both sites are located on the Blue Ridge Parkway. Ozone was also monitored at the Horton Air Pollution Research Station. This site is located near the summit of Salt Pond Mountain at an elevation of about 975 m. A monitoring station was also established near the VPI&SU campus at an elevation of about 600 m. Measurements of ambient ozone concentrations were made in 1982 for periods from May through December at the Big Meadows, Horton Station, and Blacksburg sites and from July through December at the Rocky Knob site.

Ambient ozone concentrations were measured with a Bendix chemiluminescent analyzer (Model 8002) at Big Meadows, the Horton Station, and Blacksburg site. A Dasibi analyzer (Model 9002) was used to monitor ozone at the Rocky Knob site. The monitors were continuously operated and data obtained on strip chart recorders. Hourly average ozone concentrations were determined from the strip charts and entered into the campus mainframe computer at VPI&SU for further analysis.

Ozone monitors received a 5-point calibration every six weeks using a Photocal Model 3000 Automated Ozone Calibrator (Columbia Scientific Industries Corp., Austin, Texas). The unit contains a stable ozone generator and an ultraviolet photometer which continuously monitors the output of the generator. The Photocal performs calibration procedures in accordance with the revision to the National Ambient Air Quality Standard 40 CFR Part 50, Federal Register.

Arrangements were made for the State Air Pollution Control Board to provide quality assurance verification of data obtained from monitors operated by VPI&SU personnel. On May 19, 1982, the state agency verified data obtained from the ozone monitor at the Rocky Knob site. However, the ozone analyzer at the Big Meadows site appeared to be out of compliance with EPA standards.

One experiment conducted May 24, 1982, at Research Triangle Park, North Carolina showed the ozone calibrators used by the State Air Pollution Control Board and VPI&SU to be in full agreement. But it appeared these two ozone calibrators differed in their capacity to compensate for changes in barometric pressure.

A second field inspection of the ozone monitor at Big Meadows on May 27, 1983 showed that the instrument was in compliance with EPA standards and the standards of the State Air Control Board. It was also shown that the ozone calibrator used by VPI&SU complied with EPA standards at all elevations and that this calibrator had provided an acceptable means for calibrating ozone monitors. Correspondence and documents verifying the calibration and quality assurance aspects of the air quality monitoring program in SNP are appended.

ii) Analysis of wet and dry deposition. Rainfall was collected at the Horton Air Pollution Research Station in order to monitor rainfall rates and to analyze the chemistry of atmospheric pollutants deposited in the wet (rain) or dry (gaseous and particulate) forms. The rainfall collector at the Horton site was one of about 150 collectors located across the United States and which constitute a national network established for monitoring regional trends of atmospheric pollution deposition. The wet and dry fall collectors at the Horton site and the national network constitute part of the monitoring effort developed by the National Atmospheric Deposition Program (NADP). The collector at the Horton station is identical to all other collectors in the NADP network and was operated in accordance with procedures outlined by the Technical Advisory Committee of NADP for collectors at all network sites.

The collectors used at all collection sites, including the Horton site, are of the wet/dry deposition type designed and manufactured by Aerochem Metrics (Model 301, Aerochem Metrics, Miami, Florida). This instrument consists of a two-container system with a moveable lid designed to expose the "wet" and cover the "dry" container during periods of precipitation, and vice versa during periods without precipitation. Recording rain gauges are also installed at each collection site.

Samples of precipitation and dry particle deposition were collected at each site according to the NADP Field Observer Instruction Manual. The samples were shipped in specially-designed containers for analysis at the Central Analytical Laboratory at the Illinois State Water Survey. Samples of precipitation at all sites were regularly collected on each Tuesday morning throughout the year. Precautions were taken to preclude changes in, or contamination of, each precipitation or dry deposition sample during collection, transport, and storage prior to analysis. Analyses were performed as soon as possible after shipment. A portion of composite samples were retained in storage for specialized studies and further reference.

All samples of precipitation and dry deposition were analyzed for the following elements, ions, or other properties: H^+, NH_4^+, K^+, Na^+, Ca^{++}, Mg^{++}, $SO_4^{=}$, NO_3^-, $PO_4^{\equiv}$, Cl^-, pH, total and free acidity or alkalinity, and electrical conductivity. The best available automated systems of analysis were used by the analytical laboratory in order to keep analytical costs as low as possible while still striving to obtain data of high quality, reliability, and biological or atmospheric relevance.

The selection of a Central Analytical Laboratory is one of the important factors underlying the success of the monitoring study done at the Horton site. The Analytical Department of the Illinois State Water Survey was selected because of its long experience in providing high quality analytical data on the chemistry of air and precipitation.

To insure that the Network data, including that from the Horton site, are of such high quality that they provide maximum credibility for a wide variety of fundamental and mission-oriented research purposes, the U.S. Geological Survey and the Environmental Protection Agency provide a variety of quality-control and quality-assurance services. These services include field tests of regional representativeness and objective tests of various sampling procedures and analytical methods, as well as blind audits and blind duplicate analyses. An annual statement of evaluation is provided by USGS-EPA and is published in the Annual Reports of the NADP monitoring network.

Data obtained by the Network are made available directly to all participating agencies as soon as possible after analyses are completed. Any portion, or all of the data, are provided upon request for any purpose of analysis or interpretation by personnel of any cooperating State Agricultural Experiment Station, United States Forest Service, or any other agency, public or private, which may wish to use the data. In addition, a highly flexible computerized printout system will store and provide the data in maximally useful forms; this will be achieved by building into the information storage and retrieval systems, provision for various types of sums, averages, correlations, time-course plots, spatial-variation plots, and other reasonable requirements of the SAES scientists and others who will analyze the data and publish their conclusions as a part of their own research programs.

The Environmental Protection Agency provides computerized information storage and retrieval services which catalogues the data generated by the NADP network, the Canadian Network for Sampling Precipitation (CANSAP), the Multistate Atmospheric Power Production Pollution Study (MAP3S), and certain specialized research networks.

b. Results and Discussion

i) Ozone concentrations. The National Ambient Air Quality Standard for ozone is established by the U.S. Environmental Protection Agency. The only standard for ozone is an hourly average concentration of 0.12 ppm not to be exceeded more than one day per year. The highest value recorded at the four sites was a peak ozone concentration of 0.125 ppm which was recorded at 1900 on May 12, 1982 at the Big Meadows site. This was the only exceedence of the 0.12 ppm benchmark which confirmed that all four sites complied with the federal ozone standard during 1982. The Big Meadows site consistently had the highest ozone concentrations. Three ozone episodes occurred there during which concentrations were between 0.10 ppm and 0.125 ppm for five or more hours. These episodes occurred on May 12-13, July 26, and October 1.

Monthly mean ozone data for May-December are shown for the four monitoring stations in Figure 2. The highest monthly mean concentrations were monitored during the summer months. From July, monthly mean concentrations of ozone progressively decreased through December. Monthly mean values during summer months ranged from 0.04 ppm to 0.06 ppm and were about 0.02 ppm during December. The decline in ozone concentrations during fall and winter months likely reflects low light levels and low temperatures which reduce the rate of photooxidative reactions in the atmosphere that produce ozone.

Ozone concentrations, during any month, were lower at low elevation sites that at high elevation sites (Fig. 2). The elevational gradient of ozone concentrations is least conspicuous during the months of June and July, when ozone is most abundant on a regional basis and December, when ozone is least abundant. The elevational gradient of ozone concentrations seems most pronounced in May when ozone levels are building following periods of low concentrations during winter.

Inspection of hourly ozone concentrations at the four monitoring sites shows that low and high elevation sites have similar ozone levels during the day. Ozone concentrations at low elevation sites drop at night. However, some of the highest ozone concentrations measured at the high elevation sites occur at night. Dissipation of ozone at low elevation sites may reflect both the termination of photooxidative reactions required for ozone formation as well as patterns of cold air drainage and inversions. The meteorological factors may cause ozone formed at low elevations to be displaced to high elevation sites at night. These results are similar to those observed in mountainous regions of the east by Berry (1964) and therefore our measurements of high ozone concentrations at high elevation sites during the night are supported by another study.

Monitoring ozone concentrations at these four sites provides information about air movement that is useful for analyzing the dispersal of air pollutants. For example, the idea that diurnal patterns of air movement lead to important differences in ozone concentrations at high and low elevation sites suggests other air pollutants may be moved during this daily cycle in a similar fashion. Thus, high elevation sites may also have higher nighttime concentrations of SO_2 and NO_x than low elevation sites.

The biological significance of high air pollution concentrations during darkness is unclear. Air pollutants must enter leaf mesophyll tissues in order to alter plant metabolism and thereby reduce plant growth. Plants are generally thought to close their stomata at night and, upon doing so, would be somewhat immune from ambient air pollutants since these agents could not be absorbed into the leaf. However, plants may not close stomata at night, or at least not completely close stomata in darkness, in which case air pollutants could be absorbed by plants. Some pollutants may stimulate stomatal opening and may thereby provide a mechanism of air pollution absorption during darkness. The toxicity of air pollutants absorbed during darkness may be due to limited translocation and the absence of detoxifying reactions which are related to photosynthetic processes. Very little information is available for contrasting the relative toxicity of a given amount of air pollution absorbed by leaves in light or in darkness.

ii) Rainfall chemistry. Rainfall has been collected at the Horton Air Pollution Research Station over the past five years. The collected samples have been analyzed chemically in order 1) to contribute to the data base developed by the National Atmospheric Deposition Program which was established to define long-term trends in rainfall chemistry across the United States, 2) to determine how rainfall chemistry at a specific site in western Virginia compares with rainfall chemistry at other sites in the eastern United States, 3) to more accurately simulate the chemical composition of artificial rain in laboratory experiments, and 4) to try and determine if air pollution from the Radford munitions factory contributes to the chemistry of rainfall in the region around the factory.

National trends in rainfall pH indicate that precipitation is most acidic in the northeast where the mean pH value is about 4.0 (Fig. 3). Rainfall becomes less acidic at sites located progressively further south and mean pH values approach 5.5 in Florida. Rainfall collected at the Horton Air Pollution Research Station helps define this pH gradient and, by so doing, indicates that the major local air pollution source, the Radford munitions factory, probably has, at this time, little significant influence on rainfall pH in western Virginia.

A more detailed analysis of rainfall chemistry for samples collected at the Horton Air Pollution Research Station is provided in reports published by the National Atmospheric Deposition Program. Since data obtained from the Horton Station are dedicated to this national monitoring network, we limit data presented in this report to those data released in the public domain by the National Atmospheric Deposition Program administrators. Data from two National Atmospheric Deposition Program reports, entitled NADP Data Report Precipitation Chemistry, Volume IV, Numbers 2 and 3, are pertinent to the time period covered by this ARO research contract. Number 3 is the most recent report issued by the National Atmospheric Deposition Program and it was released in October, 1983.

The precipitation depth, as well as pH values, and Ca^{++}, NO_3^-, and $SO_4^=$ concentrations for samples collected on a weekly basis from July, 1980 to July, 1981 are shown in Figure 4. In addition, detailed chemical analysis for weekly samples collected from April, 1981 to July, 1981 are shown in Figure 5 and from July, 1981 to October, 1981 are shown in Figure 6.

Rainfall pH from July, 1980 to July, 1981 ranged between 6.4 and 3.5. The mean value was about 4.5. Only three samples had values higher than 5.5. Samples which had these high pH values were enriched in Ca^{++}, NO_3^- and $SO_4^=$. However, other rainfall samples also enriched in these chemicals had pH values less than 5.5, so pH was not solely determined by Ca^{++}, NO_3^- and $SO_4^=$ content.

Samples collected from April through October in 1981 had a much smaller range of pH values with the highest reading being 5.5 and the lowest being 4.0 (Figs. 5 and 6). The mean value of 4.4 for this period was similar to the mean for the period from July, 1980 to July, 1981 (Fig. 4). We conclude, from data gathered with samples obtained at the Horton Air Pollution Research station and released by the National Atmospheric Deposition Program, that there were no clear seasonal trends in rainfall pH values. In addition, rainfall collected from this site, when compared to samples collected within the region, were not enriched in any chemical constituents which might be associated with the Radford munitions factory.

3. DEVELOPMENT OF A RAINFALL SIMULATOR

Forests and agricultural plants are exposed to air pollutants which are deposited in both the dry form, as gases, and the wet form, as precipitation. Part of our approach to studying the impact of air pollutants on plants in western Virginia is based upon laboratory experiments in which plants are exposed to pollutants in both the gaseous and liquid phases. The Continuously-Stirred Tank Reactors (CSTR's) at the Laboratory for Air Pollution Impact to Agriculture and Forestry has proven to be a reliable method for fumigating plants with gaseous ozone, SO_2, and NO_x. Since we desired to apply simulated rainfall on plants in controlled laboratory experiments, we designed and constructed an indoor rainfall simulator. This rainfall simulator has worked reliably and helped us more accurately recreate, in laboratory experiments, the air pollution stress which plants encounter in nature.

a. Materials and Design

A rainfall simulator system was developed on the principal of droplet formation from capillary tubes. The system consists of a steel frame structure supporting a centrally-positioned hub containing eight radially-arranged tubes (Figure 7). The hub and radial tubes are constructed from polyvinyl chloride pipe (pvc) and are nearly inert to solutions of moderate to low acidity (> pH 3.0). Droplet formation is produced by hypodermic needles positioned linearly along the bottom of each tube. A circular table (1.9 cm plywood), 1.2 m dia, is centered below a rainfall dispensing system. The table, upon which experimental plant material is placed, revolves at 2 rpm driven by a 1/20 hp gear electric motor positioned below the table. A variable speed peristaltic pump is used to uniformly supply artificial rain to individual tygon lines. Each line delivers simulated rain from a holding tank to the hub of a rainfall simulation unit. The pump lines are connected to each unit by tubing and simulated rain is drawn from 501 polypropylene carboys.

To achieve uniform rainfall from a single tube positioned along the radius of a circular target area, an empirical cumulative probability distribution of the rainfall was used. To further enhance the uniformity of rainfall, the needle placement on two sets of four tubes was staggered, presenting a spiral arrangement of needles on all eight tubes when viewed from below. The central hub prevented the use of the entire length of a radial tube for needle placement such that 21 needles were positioned along each tube for a total of 168 needles per 1.1 m^2 target area.

b. Performance Characterization

Droplet formation from the tips of hypodermic needles and droplet geometry are shown in Figure 8. Droplets appeared spherical immediately upon separation from the needle tips and droplet diameter was measured when the distance between needle tip and a falling drop was < 10 cm. Droplet diameter as a function of needle gauge was very uniform (Table 1) with coefficients of variation ranging from 2.7 to 3.1%. Needles gauge 20, 21 and 22 produced droplets with mean diameters of 3.3, 2.9 and 2.6 mm, respectively.

The rainfall intensities attainable by the system were controlled by a variable speed pump drive and ranged from 0.5 to 1.25 cm h^{-1}. Rainfall distribution across the target area was uniform at various flow rates during 1 h simulated rain events (Table 2). Coefficients of variation ranged from 2.5 to 4.0% for rain intensities of 0.99, 0.85 and 0.65 cm h^{-1}. Rainfall distribution among simulation units at various flow rates was also uniform (Table 3). At three different rain intensities, coefficients of variation among three target tables ranged from 1.2 to 2.6%.

The pH and conductivity of simulated rain solutions remained stable upon passing through the rain simulation apparatus (Table 4). At low pHs, 3.04 and 4.35, no change in pH occurred in solutions collected at 30- and 60-min intervals. As the hydrogen ion concentration decreased, pH 5.83, the system caused a slight acidification of the simulated rain. Changes in pH, however, were less than 0.2 pH units. The conductivity of solutions at pHs 5.83 and 4.35 did not change appreciably upon passage through the simulator. Maximum differences of 9 μmohs cm^{-1} (2.1%) were found at pH 3.04 between stock solutions and samples collected from the simulator.

Changes in other major ion concentrations attributable to the simulator varied depending upon the ionic species (Table 5). Calcium, Mg^{++} and K^{+} concentrations remained nearly constant, with maximum variation between stock solution and samples of 4.2, 3.2 and 2.9%, respectively. Concentration of the ammonium ion varied the greatest and a decrease in concentration occurred as the duration of a rain event increased. At 30 min, differences in NH_4^{+} concentrations between stock solutions and samples were 3.5%, but this increased to 19% after 60 min. Concentrations of the anions Cl^{-}, NO_3^{-} and $SO_4^{=}$ were minimally altered by the rain simulator (Table 5) with variation in concentration between the stock solution and 60 min samples being 4.3, 2.9 and 3.6%, respectively. At high sulfate concentrations, in pH 3.0 solutions, no difference was found between the stock solution and a 60-min sample.

4. MEASUREMENTS OF PLANT RESPONSES TO AIR POLLUTION

Ozone, at the present time, is a potential threat to forest vigor in the United States. Amongst many forest species, white ash (*Fraxinus americana* L.) is important to the forest industry in the eastern U.S., is commonly found in the forested areas of the southern Appalachian Mountains, and is classified as being relatively sensitive to ozone. Given the abundance and economic importance of this species, we devised field fumigation experiments to deterine the effects of ambient ozone concentrations on the growth of white ash seedlings.

Individual trees within a population vary in air pollution sensitivity and this poses problems for those managing forest resources. For example, trees which are tolerant of ambient pollutants may not be economically desirable in managed forests. This sort of variation in air pollution tolerance amongst species in unmanaged forests may lead to changes in population structures, species richness, and genetic pool size of native plant communities.

Here we describe the results of a series of field experiments conducted with white ash seedlings. The seedlings were raised in the presence, or absence, of ambient pollutants at two sites in southwestern Virginia. The purpose of these experiments was to evaluate the sensitivity of white ash seedlings to ambient pollutants, and after evaluating visible foliar injury and growth reactions due to pollutants, we aim to define the relative air pollution sensitivity of this species.

a. Experimental Methods

Two field research sites were established at 1) the Poultry Science Research Farm (PSF), Blacksburg, Montgomery Co., Virginia, elevation 610 m, and 2) the Horton Air Pollution Research Station (HC), Salt Pond Mountain, Giles Co., Virginia, elevation 945 m, during the summer of 1981. The Poultry Research Farm is located 15 km northeast of the RAAP and during the summer months is directly downwind from the arsenal. The Horton Research Center is located 28 km to the north of the RAAP and is separated from it by two intervening ridges of mountains, and is representative of the mountainous regions of southwestern Virginia.

Six open-top chambers were used at each site. These chambers were cylindrical, measure 2.5 m high and 3 m in diameter, and consisted of an aluminum frame covered with plastic panels. The chambers were placed at each site with two chambers each receiving charcoal-filtered air (CFC), which was nearly pollution-free, ambient air (UFC, dust filter only), and plots with no chambers (AP). Ozone concentrations in each chamber were monitored (Table 1), with the average ozone removal efficiency of the charcoal-filtered chambers being approximately 70% at both sites.

White ash (*Fraxinus americana* L.) seedlings collected from natural populations (1-0 nursery stock, Ohio State Nursery, Delaware, Ohio) were planted within each chamber during July, 1981 in a circular pattern, 0.3 m apart and 1.5 m from the center of the chamber. Five trees each were arbitrarily designated as large, medium, or small at the time of planting in each chamber. Increase in tree height and diameter were not recorded during the 1981 growing season because the trees were still recovering from transplant shock.

Tree height was measured from the ground line to the base of the terminal bud at bi-weekly intervals and stem diameter, measured at 10 cm above the ground line was recorded monthly during the April-September growing season. Growth rates and total growth were determined from these data.

At the termination of the growing season, but before leaf absicission, all leaves were counted on each tree. Also, the number of leaves exhibiting visible symptoms of ozone injury (purple stipples or adaxial leaf surface) were recorded. Leaves were then brought to the laboratory and dried at 70°C for 36 h and foliar dry weight was determined.

b. Results and Discussion

The significance of the F-ratio values for growth and foliar symptoms data obtained from our experiments, as determined from Analyses of Variance procedures are shown in Table 2. Trees grew at significantly different rates depending upon site and initial height at planting. The only significant treatment (open-top chamber) effects were with average rate of height growth and the percent symptomatic leaves. There was a site x treatment interaction with leaf weight and no significant interactions with treatment x initial planting height.

i) Height and diameter growth. Trees at the two sites were growing under different edaphic conditions (Table 3), climatic conditions (not reported but PSF is 300 m lower in elevation than HC), and average ozone concentrations as reported in a previous section of this report. Trees growing at the Poultry Science Research Farm (PSF) exhibited faster growth rates and greater total height and diameter increase than trees growing at the Horton Air Pollution Research Station (HC) as shown in Tables 4 and 5.

The average bi-weekly height growth increase was 10.9, 10.2 and 7.0 cm for UFC, CFC and AP, respectively. Trees growing in AP had significantly lower rates of shoot growth when compared with those in UFC and CFC (Tukey's studentized range test). Leaves exhibiting visible ozone injury symptoms were 54.2, 28.5 and 13.7% for AP, UFC and CFC, respectively, and these values were significantly different from each other.

Trees in the large category at time of planting, irregardless of site, grew in height at a significantly faster rate (approximately 40%) than trees in either the medium or small groups and had a 30% and 40% greater total height increase than trees in the medium or small categories, respectively.

Average leaf weights at PSF were 44.4, 36.2 and 31.0 g for trees in CFC, UFC and AP, respectively, but at HC leaf weights were 20.5, 15.9 and 14.7 g for UFC, AP and CFC, respectively. This is a reversal in weights between treatments depending upon site.

The average height growth (cm) and average diameter growth (mm) are shown in Tables 4 and 5, respectively, by site and height category. Trees at PSF in the large category generally had a faster rate of height growth (Table 4) in CFC than did trees in UFC or AP. Also, total height increase for large trees in CFC was 9 and 43% greater than for trees in UFC or AP, respectively. There were no significant differences in growth rate or total height increase for trees in medium or small categories at PSF. Large trees at HC in UFC grew at a faster rate and had greater total height increase than trees in CFC or AP. Similar results were observed for trees in the medium category. Trees in the small category exhibited greater total height increase in CFC compared to trees growing in AP.

Unlike height growth (Table 4) the results for average diameter increase (Table 5) indicate only slight differences between treatments for trees in one particular category at either site. Significant differences in diameter growth were observed for trees in the small category at HC. Trees in CFC grew at a significantly greater rate and had greater total diameter increase than trees in UFC.

ii) Foliar symptoms. The prevalence (percent symptomatic seedlings) and severity (percent symptomatic leaves) are shown in Table 6, by site and initial height at time of planting. Trees in all size classes which were growing in AP generally had the greatest amounts of visible foliar ozone injury. The only exception was for large trees growing in CFC at HC. These trees had more visible foliar ozone injury than did trees growing in UFC.

Multiple linear regression was used to determine if the percentage of visible injured leaves (regressor) was related to total height increase (response). The R^2 values were low (< 20%), and only trees in the large category and trees growing at PSF, irrespective of initial size had F-ratios which were significant ($P = 0.06$ and $P = 0.01$, respectively). These broad correlations between visible foliar injury and reductions in height growth for large trees are tentative but imply that foliar injury may reduce primary shoot growth.

c. Summary

Tree growth rates were influenced by the planting location and by initial tree size at planting time. Trees at PSF grew significantly larger than trees at HC. Large trees at both sites grew better than small or medium-sized trees. The average rate of height growth was significantly greater for trees in CFC and UFC than for trees growing at AP. This pattern suggests that environmental factors, such as light, humidity, and temperature, in the chambers differ from those outside chambers. These environmental differences are reflected in tree growth patterns. Diameter growth was not significantly different between treatments. Prevalence and severity of foliar ozone injury was generally the greatest for trees growing in AP and the least for trees growing in CFC. The variation in response between treatments was the greatest for lage trees indicating that larger, faster-growing specimens of this species may be relatively more vulnerable to ambient air pollution. There appears to be a broad correlation between visible foliar ozone injury and reductions in the growth rates of large trees which indicates that visible ozone symptoms on leaves may be partially responsible for a reduction in height increase.

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C. TABLES

Table 1. Relationship of rain droplet size to needle gauge at a rainfall intensity 0.85 cm h^{-1}.

Needle gauge	I.D. (mm)	O.D. (mm)	Droplet diameter (mm) Mean[a]	Range
20	0.58	0.89	3.27 ±0.10	3.1-3.4
21	0.56	0.81	2.90 ±0.08	2.8-3.0
22	0.45	0.71	2.57 ±0.07	2.5-2.7

[a]Mean and standard deviation of seven droplets each from 20 and 21 gauge needles and ten droplets from 22 gauge needles.

Table 2. Simulated rainfall distribution over a target area during 1 hr rain events.

	Rain intensity (cm h^{-1})		
	0.99	0.85	0.65
Sample #	Rainfall collected (ml)		
1[a]	57	47	37
2	55	47	39
3	56	49	38
4	57	44	38
5	58	47	37
6	57	46	37
7	55	50	37
8	55	49	34
9	59	50	37
10	58	47	37
Mean	56.7	47.6	37.1
S.D.	±1.4	±1.9	±1.3

[a]Collection beakers, 8.5 cm dia, were positioned along two radii of the target area.

Table 3. Simulated rainfall distribution among three acid rain simulation units during a 1-hr rain event.

	Rain intensity (cm h^{-1})		
	0.99	0.85	0.65
	Rainfall collected (ml)		
Unit 1[a]	56.4 ±1.1	48.0 ±2.2	37.0 ±1.3
Unit 2	53.6 ±2.5	48.8 ±4.0	37.1 ±3.5
Unit 3	54.5 ±2.6	49.2 ±1.3	38.0 ±1.4

[a]Collection beakers, 8.5 cm in diameter, were positioned along four radii on the target area. Each value represents the mean and one standard deviation of 20 samples.

Table 4. Solution pH and conductivity of simulated rain before and after passing through the rain simulator.

Sampling time (min)	pH	H^+ μeq l^{-1}	Conductivity (μmohs cm^{-1})
0[a]	5.83[b]	1.5 ± 0.3[c]	30.0 ± 0.7
30	5.65	2.3 ± 0.5	29.6 ± 1.5
60	5.71	2.0 ± 0.3	28.2 ± 0.8
0	4.35	45.1 ± 1.6	42.4 ± 0.9
30	4.33	46.4 ± 1.6	42.0 ± 1.0
60	4.35	44.9 ± 1.3	40.0 ± 1.4
0	3.04	905.3 ± 60.7	425.0 ± 15.0
30	3.04	916.6 ± 27.6	418.0 ± 4.5
60	3.04	908.8 ± 17.5	416.0 ± 5.5

[a]Sample collected from stock solution.

[b]All values are means of five samples.

[c]Indicates one standard deviation.

Table 5. Major ion chemistry of simulated rain before and after passing through the rain simulator[a].

	Stock solution	30 min sample	60 min sample
pH	4.52	4.62	4.53
H^+ μeq l^{-1}	30.0 ±3.0	24.1 ±2.2	29.9 ±3.3
Conductivity (μmohs cm^{-1})	15.0 ±0.4	15.3 ±0.8	14.0 ±1.2
Calcium[b]	0.95 ±0.05	0.91 ±0.11	0.94 ±0.12
Magnesium	0.095 ±0.003	0.098 ±0.006	0.097 ±0.004
Ammonium	0.58 ±0.02	0.56 ±0.05	0.47 ±0.05
Potassium	0.34 ±0.001	0.34 ±0.001	0.35 ±0.002
Chloride	0.44 ±0.02	----	0.46 ±0.04
Nitrate	5.25 ±0.23	----	5.40 ±0.33
Sulfate[c]	4.76 ±0.18	----	4.93 ±0.19
(pH 3.00)	60.6 ±3.3	----	60.7 ±5.7

[a] Phosphate concentrations were below the detection limit of the ion chromatograph, sodium data were not included due to contamination during collection procedures, cation concentrations were determined on a solution of pH 4.50 and represent 5 replicate samples, anion concentrations were determined on solutions of pH 4.30 and 5.67 and represent 5 replicate samples, with one standard deviation.

[b] Ion concentrations expressed in mg l^{-1}.

[c] Sulfate concentrations were determined on solutions of pH 5.67, 4.30 (no addition of H_2SO_4) and 3.00 (H_2SO_4 added to adjust pH) and represent 3 replicate samples.

Table 6. Ozone concentrations (ppm) on 23 June 1982 for charcoal-filtered (CFC), unfiltered (UFC) and ambient plots (AP) for two locations in southwestern Virginia.

	Location					
	Poultry Science Research Farm			Horton Research Center		
	Replication			Replication		
Treatment	1	2	Average	1	2	Average
CFC	0.02	0.01	0.01	0.01	0.02	0.01
UFC	0.04	0.05	0.04	0.05	0.05	0.05
AP	0.05	0.05	0.05	0.05	0.04	0.04

[a]Concentrations = average of five readings.

Table 7. Results of analysis of variance on growth and visible symptoms of 3-year-old *Fraxinus americana* seedlings growing in open-top chambers from April-September, 1982 at two sites in southwestern Virginia.

Source[a]	Significance of F-ratios[b]					
	Height increase (cm)[c]		Diameter increase (mm)[d]		Leaf weight (g)	Percent symptomatic leaves
	Ave. rate	Total	Ave. rate	Total		
Site	**	*	**	**	**	NS
Replication	NS	NS	NS	NS	NS	NS
Treatment	*	NS	NS	NS	NS	*
Height group	**	**	NS	NS	**	NS
Site x treatment	NS	NS	NS	NS	**	NS
Treatment x group	NS	NS	NS	NS	NS	NS

[a]Site = Poultry Science Research Farm and Horton Research Center; treatment = charcoal-filtered air, unfiltered air and ambient air; height group = large, medium or small trees, 20 each per treatment, 180 total trees.

[b]* = significant at 0.05; ** = significant at 0.01; NS = non-significant.

[c]Ave. rate = average biweekly rate of height increase.

[d]Ave. rate = average monthly rate of dia. increase 10 cm above ground line.

Table 8. Soil parameters measured from 10-30 cm depth at two sites in southwestern Virginia.

	Variables analyzed[a]									
		lb/A				ppm				
Location[b]	pH	Ca	Mg	P	K	Zn	Mn	NO_3-N	soluble salts	organic matter %
PSF	5.8a	574.5a	64.0a	8.5a	44.0a	1.9a	6.8a	4.2a	8.5a	1.7a
HC	6.1b	751.5b	96.7b	17.5b	60.0b	1.6a	15.9b	3.0a	107.5b	1.9a

[a]Different letters indicate that values are significantly different ($p = 0.05$) according to Tukey's studentized range test.

[b]PSF = Poultry Science Research Farm; HC = Horton Research Center.

Table 9. Average height growth increase (cm) of *Fraxinus americana* seedlings from April-September, 1982 in charcoal-filtered (CFC) and unfiltered (UFC) chambers, and ambient plots (AP) at two locations in southwestern Virginia.

	Location					
	Poultry Science Research Farm			Horton Research Center		
	Seedling size[a]			Seedling size[a]		
Treatment[b]	Large	Medium	Small	Large	Medium	Small
	Average rate of growth (cm)[c]					
CFC	19.9a	11.8a	11.4a	8.0ab	5.8ab	
UFC	18.4a	12.8a	10.5a	13.5a	8.3a	
AP	11.4b	8.9a	7.7a	5.6b	4.7b	
	Total growth (cm)[d]					
CFC	106.5a	63.3a	59.7a	45.0b	40.0ab	
UFC	96.4ab	67.9a	53.5a	78.1a	52.4a	
AP	59.7b	48.7a	45.7a	34.1b	22.0b	

[a]Trees were assigned to three categories by initial height at time of planting.

[b]Different letters indicate that values are significantly different (p = 0.050 according to Tukey's studentized range test.

[c]Average rate of growth = the average biweekly growth rate during the 10-week period of maximum growth (week 2-12; week = initial of observation).

[d]Total growth = average growth increase for entire growing season.

Table 10. Average diameter growth increase (mm) of *Fraxinus americana* seedlings from April-September, 1982 in charcoal-filtered (CFC) and unfiltered (UFC) chambers, and ambient plots (AP) at two locations in southwestern Virginia.

	Location					
	Poultry Science Research Farm			Horton Research Center		
	Seedling size[a]			Seedling size[a]		
Treatment[b]	Large	Medium	Small	Large	Medium	Small
	Average rate of growth (cm)[c]					
CFC	1.4a	1.3a	1.3a	0.7a	0.6a	0.8
UFC	1.5a	1.3a	1.1a	0.9a	0.8a	0.5
AP	1.3a	1.0a	1.1a	0.9a	0.9a	0.7
	Total growth (mm)[d]					
CFC	7.1a	7.1a	6.8a	3.6a	3.2a	4.2
UFC	7.4a	6.9a	5.6a	4.3a	3.8a	2.3
AP	7.1a	5.3a	5.6a	4.1a	4.5a	3.7

[a]Trees were assigned to three categories by initial height at time of planting.

[b]Different letters indicate that values are significantly different (p = 0.050 according to Tukey's studentized range test.

[c]Average rate of growth = the average monthly growth rate during the 5-month growing season.

[d]Total growth = average growth increase for entire growing season.

Table 11. The percent ozone symptomatic _Fraxinus americana_ seedlings and leaves observed at termination of growing season (September, 1982) in charcoal-filtered (CFC) and unfiltered (UFC) chambers and ambient plots (AP) at two locations in southwestern Virginia.

	Location					
	Poultry Science Research Farm			Horton Research Center		
	Seedling size[a]			Seedling size[a]		
Treatment[b]	Large	Medium	Small	Large	Medium	Small
	Percent symptomatic seedlings[a]					
CFC	50	60	30	90	20	0
UFC	70	60	70	60	50	80
AP	100	100	100	100	90	100
	Percent symptomatic leaves[d]					
CFC	14a	27a	3a	32a	5a	0a
UFC	31ab	23a	35b	31a	17ab	35b
AP	58b	62b	85c	52a	33b	36b

[a]Trees were assigned to three categories by initial height at time of planting.

[b]Different letters indicate that values are significantly different ($p = 0.05$) according to Tukey's studentized range test; percent symptomatic seedlings were not statistically analyzed.

[c]Percent symptomatic seedlings = number of seedlings with symptoms/total number of seedlings x 100.

[d]Percent symptomatic leaves = number of leaves with symptoms/total number of leaves x 100.

D. FIGURE LEGENDS

Figure 1. Location of ozone monitoring stations (numbers 1, 2, 3 and 4) and rainfall collection stations (number 3) operated by the Laboratory for Air Pollution Impact to Agriculture and Forestry. The sites are identified as follows: 1 = Shenandoah National Park (Big Meadows) site; 2 = Rocky Knob site, 3 = Horton Air Pollution Research Station and 4 = Blacksburg site.

Figure 2. Monthly mean ozone concentrations, calculated from 24 h daily mean values, for May-December, 1982. Concentrations are shown for four sites with different elevations including the site at Blacksburg (B), Rocky Knob (RK), the Horton Station (HS), and Shenandoah National Park (S).

Figure 3. Isobars showing trends in rainfall acidity (pH values) across the United States.

Figure 4. Weekly precipitation rates (PPT cm) during which samples were collected and analyzed for acidity (pH) and concentrations (mg/L) of Ca, NO_3, and SO_4. Samples obtained from the Horton Air Pollution Research Station from July, 1980 to July, 1981 and published in the NADP Report, Precipitation Chemistry (Volume IV, Number 2).

Figure 5. Characteristics of rainfall, including depth and chemical analyses, for samples collected on a weekly basis from the Horton Air Pollution Research Station. Samples were collected from April, 1981 to July, 1981 and analyses were published in the NADP Data Report, Precipitation Chemistry (Volume 4, Number 2).

Figure 6. Characteristics of rainfall, including depth and chemical analysis, for samples collected on a weekly basis from the Horton Air Pollution Research Station. Samples were collected from July, 1981 to October, 1981 and analyses were published in the NADP Data Report, Precipitation Chemistry (Volume 4, Number 3).

Figure 7. Schematic diagram of a rainfall simulation unit; a) central hub, b) radial tubes containing hypodermic needles, c) structural supports, d) rotating table, e) 1/20 pH gear motor, f) tube indicating hydrostatic pressure. Inset: schematic aerial view of entire rainfall simulator system a) peristaltic pump, b) carboy containing rain solutions, c) rainfall simulation apparatus.

Figure 8. Droplet formation from the tips of a) 22 gauge, b) 21 gauge and c) 20 gauge needles (bars = 1 mm).

E. FIGURES

Fig. 1

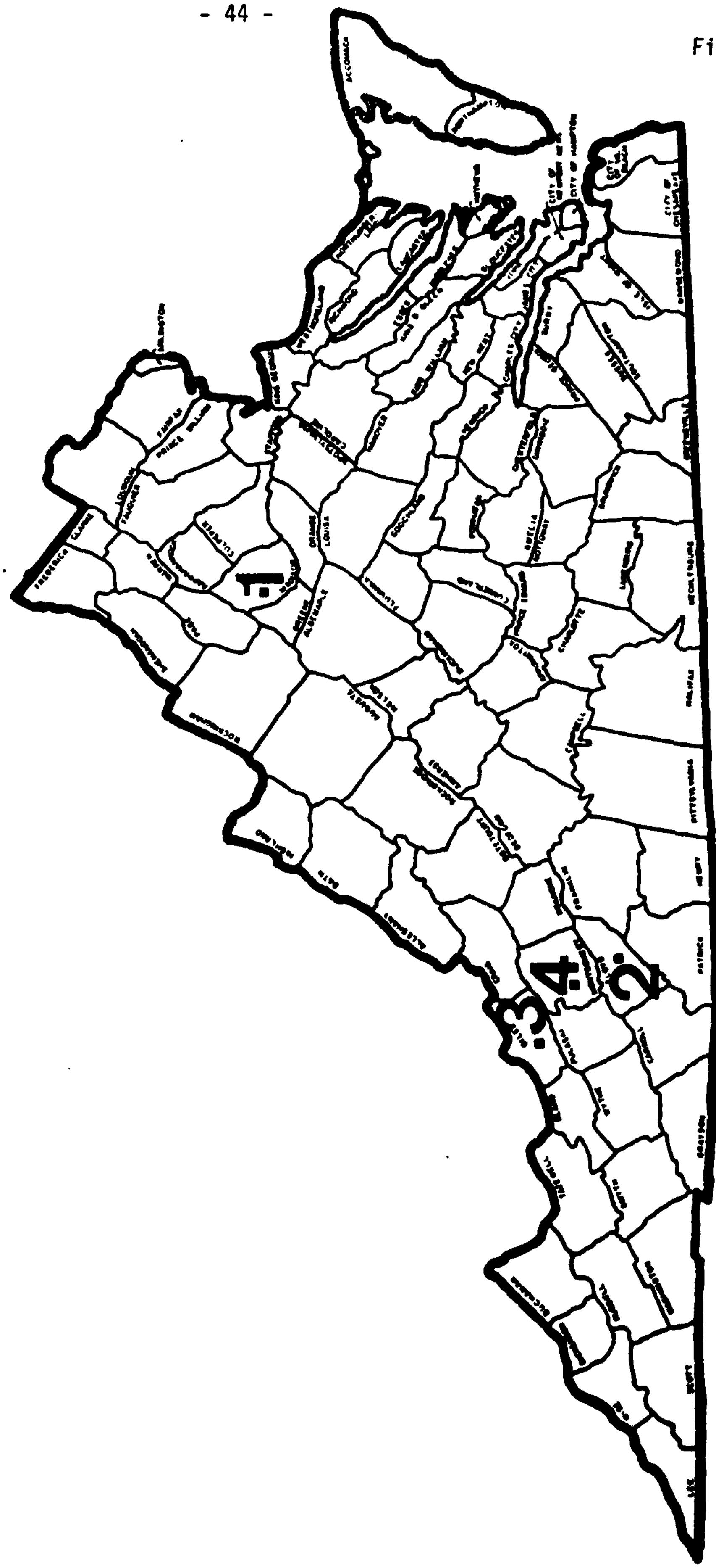


Fig. 2

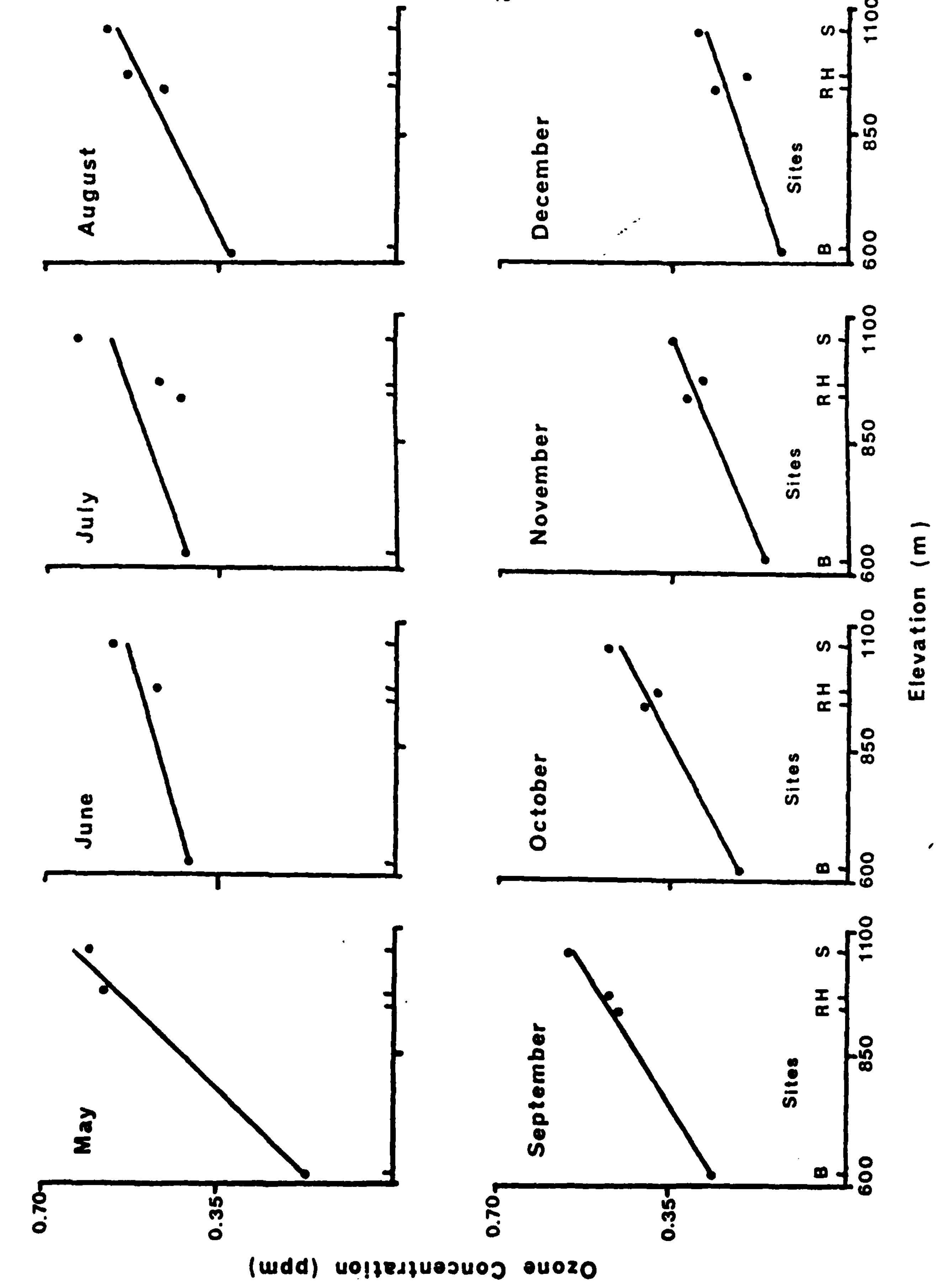

May
June
July
August
September
October
November
December
Ozone Concentration (ppm)
0.70
0.35
Sites
B
R H
S
600
850
1100
Elevation (m)

Fig. 3

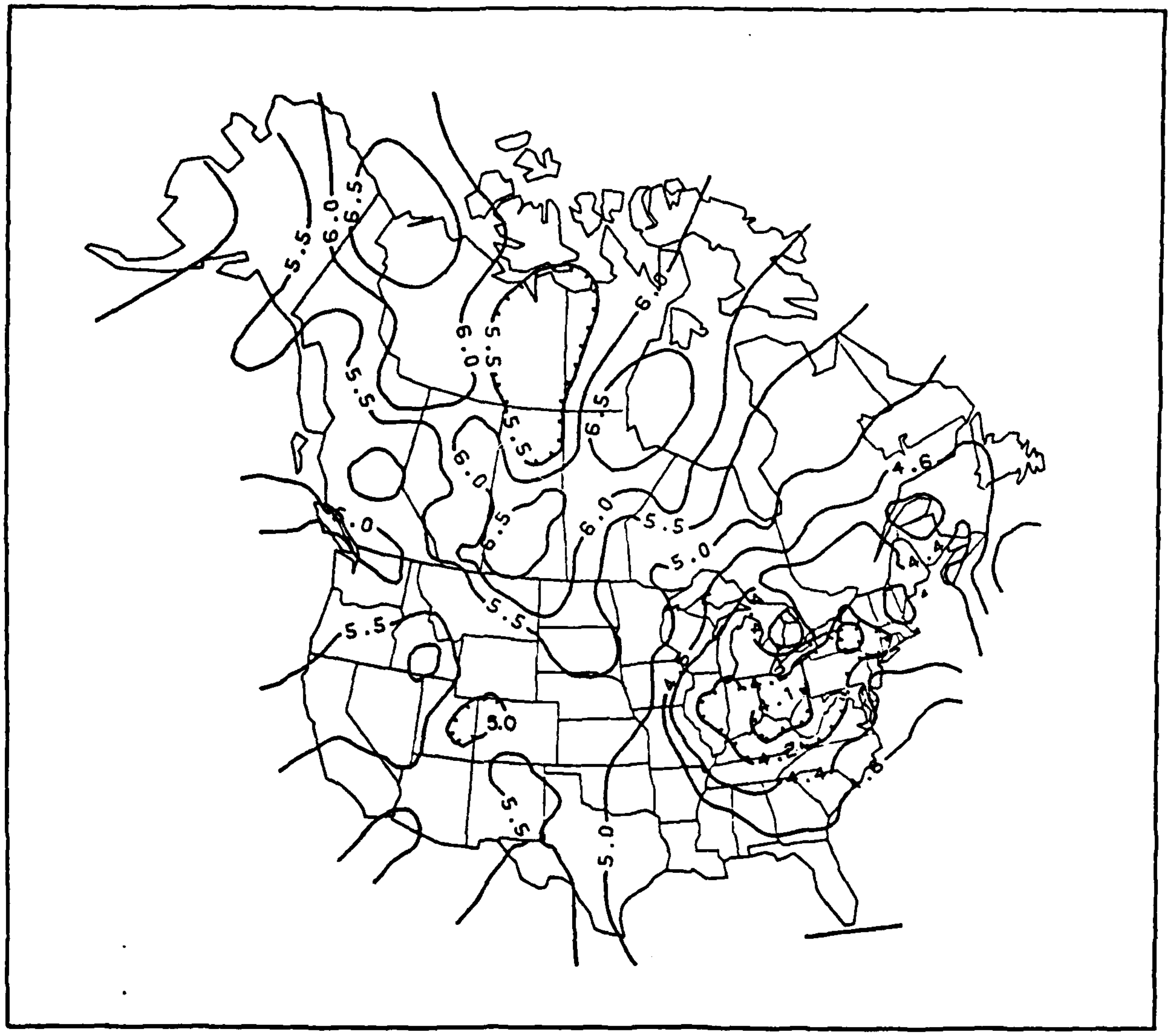
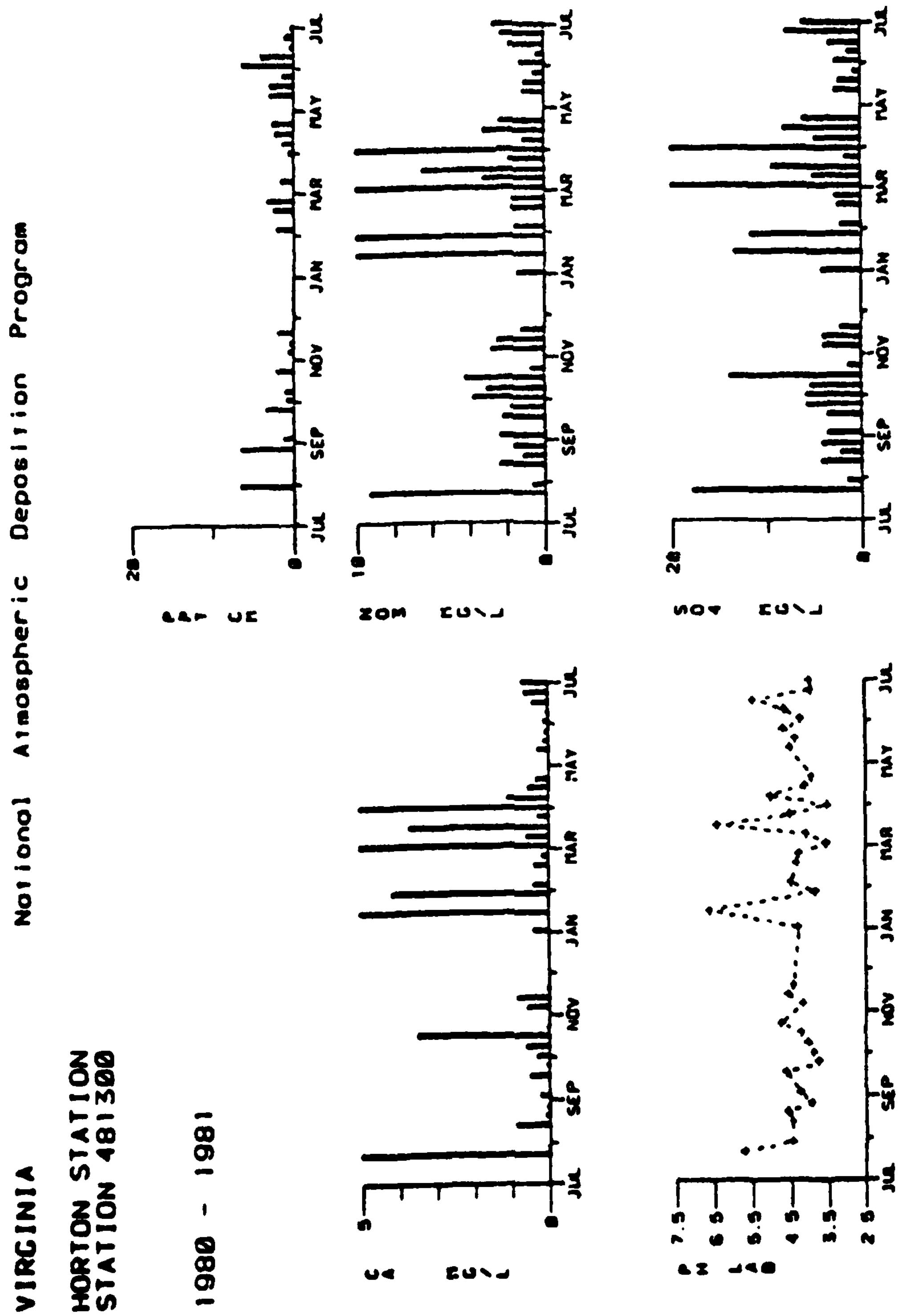


Fig. 4



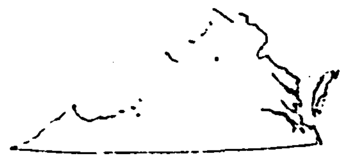
National Atmospheric Deposition Program
VIRGINIA
HORTON STATION
STATION 481300
1980 - 1981
JUL SEP NOV JAN MAR MAY JUL
7.5 6.5 5.5 4.5 3.5 2.5

NATIONAL ATMOSPHERIC DEPOSITION PROGRAM

STATE : VIRGINIA

STATION : MORTON STATION
COUNTY : GILES COUNTY
AGENCY : SAES-VPI & STATE UNIVERSITY
PRINTED : AUG 26, 1983

STATION # 481300
ELEVATION 1058 METERS
LONG. 80:25, LAT. 37:11



WET SAMPLES - WEEKLY

	DATE ON MODAYR	DATE OFF MODAYR	LAB PH	LAB CONDUCTIVITY MICRO S/CM	SAMPLER VOL L	SAMPLER DEP CM	RAIN GAGE CM	COLL EFF	LAB TYPE (1)	NOTES (2)	TIME ON GMT	TIME OFF GMT	OBS
•	33181	40781	5.03	22.2	.484	.71	1.22	.58	W	BU	1200	1200	JPS
•	40781	41481	4.14	55.6	.857	1.26	2.08	.61	W	BU	1200	1400	JPS
•	41481	42181	3.98	52.7	1.549	2.28	2.41	.95	W	BU	1400	1200	JPS
•	42181	42881	--	--	--	--	.10	--	DA	BU NA	1200	1300	JPS
•	42881	50581	--	--	--	--	.86	--	DA	BU NA	1300	1100	JPS
•	50581	51281	4.52	21.1	1.699	2.50	2.79	.90	W	BU	1100	1300	JPS
	51281	51981	4.37	24.0	2.064	3.04	2.85	1.07	W		1300	1900	JPS
	51981	52681	4.71	12.2	.818	1.21	1.17	1.03	W		1900	1100	JPS
	52681	60281	4.24	28.8	4.180	6.16	6.17	1.00	W		1100	1900	JPS
	60281	60981	4.65	13.6	2.711	3.99	3.94	1.01	W		1900	1000	JPS
	60981	61681	5.47	16.8	.253	.37	.36	1.05	W		1000	1100	JPS
	61681	62381	3.97	61.6	.654	.96	.97	1.00	W		1100	1615	JPS
	62381	63081	4.00	55.0	.225	.33	.28	1.19	W		1615	1405	DG
	63081	70781	4.05	44.7	3.222	4.75	4.29	1.11	W		1405	1950	DG

SEE TABLE EXPLANATIONS (1),(2)

-- INDICATES MISSING DATA
• INDICATES BULK SAMPLE

CONCENTRATIONS (MILLIGRAMS PER LITER FOR THE SAMPLE PERIOD)

DATE ON	DATE OFF	CA	MG	K	NA	NH4	NO3	CL	SO4	PO4	H	CATION	ANION	RATIO
33181	40781	1.06	.156	.125	.219	.63	1.14	.24	4.90	< .003	9.33E-3	122.8	127.3	1.0
40781	41481	.53	.138	.277	.357	1.66	3.17	.56	8.25	.110	7.24E-2	225.0	242.2	.9
41481	42181	.34	.091	.141	.253	.62	2.42	.41	6.27	.013	1.05E-1	178.2	181.6	1.0
42181	42881	--	--	--	--	--	--	--	--	--	--	--	--	--
42881	50581	--	--	--	--	--	--	--	--	--	--	--	--	--
50581	51281	.30	.086	.093	.120	.35	1.16	.19	2.84	< .003	3.02E-2	79.3	83.3	1.0
51281	51981	.12	.016	.030	.032	.29	1.07	.09	2.38	< .003	4.27E-2	68.2	69.4	1.0
51981	52681	.09	.019	.013	.025	< .01	.58	.06	.85	< .003	1.95E-2	27.5	28.8	1.0
52681	60281	.12	.015	.024	.054	.22	1.34	.11	2.82	< .003	5.75E-2	79.9	83.5	1.0
60281	60981	.07	.015	.010	.023	.06	.45	.04	1.34	< .003	2.24E-2	31.7	36.4	.9
60981	61681	.41	.100	1.170	.087	.13	1.87	.15	3.27	.004	3.39E-3	73.0	102.6	.7
61681	62381	.53	.099	.042	.418	.87	2.33	.21	7.85	< .003	1.07E-1	214.3	207.0	1.0
62381	63081	.71	.127	.296	.107	.21	2.76	.28	6.33	< .003	1.00E-1	169.8	184.3	.9
63081	70781	.13	.043	.012	.060	.29	1.76	.16	4.43	< .003	8.91E-2	119.8	125.2	1.0

NOTE - SULPHATE AS SO4; NITRATE AS NO3; AMMONIUM AS NH4; PHOSPHATE AS PO4

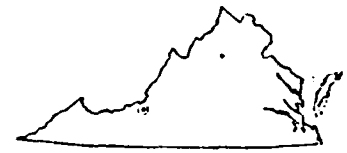
Fig. 5

NATIONAL ATMOSPHERIC DEPOSITION PROGRAM

STATE : VIRGINIA

STATION : HORTON STATION
COUNTY : GILES COUNTY
AGENCY : SAES-VPI & STATE UNIVERSITY
PRINTED : OCT 28, 1983

STATION # 481300
ELEVATION 1058 METERS
LONG. 80:25, LAT. 37:11



WET SAMPLES - WEEKLY

DATE ON MODAYR	DATE OFF MODAYR	LAB PH	LAB CONDUCTIVITY MICRO S/CM	SAMPLER VOL L	SAMPLER DEP CM	RAIN GAGE CM	COLL EFF	LAB TYPE (1)	NOTES (2)	TIME ON GMT	TIME OFF GMT	OBS
63081	70781	4.05	44.7	3.222	4.75	4.29	1.11	W	SP	1405	1950	DG
70781	71481	4.04	50.8	1.903	2.80	--	--	W	SP	1950	2100	JPS
71481	72181	4.08	44.3	2.966	4.37	4.45	.98	W	SP	2100	1100	JPS
72181	72881	4.18	41.2	1.192	1.76	2.03	.86	W	SP	1100	2230	DG
72881	80481	4.63	25.7	.137	.20	--	--	W	SP	2230	1545	DG
80481	81181	4.60	19.2	1.085	1.60	1.52	1.05	W	SP	1545	1420	DG
81181	81881	4.05	56.0	.616	.91	1.02	.89	W	SP	1420	1440	DG
81881	82581	--	--	--	--	0.00	--	DA	NA SP	1440	1450	DG
82581	90181	4.57	26.3	1.282	1.89	1.91	.99	W	SP	1450	1340	DG
90181	90881	4.28	28.2	6.913	10.18	8.76	1.16	W	SP	1340	1545	DC
90881	91581	4.03	60.5	.289	.43	.38	1.12	W	SP	1545	1415	DG
91581	92281	4.57	19.8	1.155	1.70	1.78	.96	W	SP	1415	1320	DG
92281	92981	--	--	.003	.00	0.00	--	T	SP	1320	1405	WEM
92981	100681	4.46	27.3	.610	.90	1.02	.88	W	SP	1405	1930	WEM

SEE TABLE EXPLANATIONS (1),(2)

-- INDICATES MISSING DATA

CONCENTRATIONS (MILLIGRAMS PER LITER FOR THE SAMPLE PERIOD)

DATE ON	DATE OFF	CA	MG	K	NA	NH4	NO3	CL	SO4	PO4	H	CATION	ANION	RATIO
63081	70781	.13	.063	.012	.060	.29	1.76	.16	4.43	< .003	8.91E-2	119.8	125.2	1.0
70781	71481	.23	.026	.024	.364	.47	2.06	.09	5.42	< .003	9.12E-2	147.4	148.7	1.0
71481	72181	.09	.028	.009	.028	.33	1.69	.04	3.69	< .003	8.32E-2	109.7	105.3	1.0
72181	72881	.26	.071	.037	.090	.28	1.47	.16	4.04	< .003	6.61E-2	105.3	112.4	.9
72881	80481	.34	.176	.047	.474	.12	1.72	.58	2.46	< .003	2.34E-2	83.4	95.4	.9
80481	81181	.11	.074	.013	.076	.05	1.13	.08	1.36	< .003	2.51E-2	43.1	48.9	.9
81181	81881	.27	.087	.054	.110	.42	1.91	.16	5.67	< .003	8.91E-2	139.2	153.5	.9
81881	82581	--	--	--	--	--	--	--	--	--	--	--	--	--
82581	90181	.11	.063	.010	.051	.17	.69	.08	1.84	< .003	2.69E-2	49.5	51.8	1.0
90181	90881	.05	.024	.012	.036	.23	1.18	.06	2.67	< .003	5.25E-2	71.6	76.4	.9
90881	91581	.28	.320	.040	.274	.43	1.72	.27	6.91	< .003	9.33E-2	170.4	179.3	1.0
91581	92281	.21	.079	.016	.055	.16	.84	.06	2.19	< .003	2.69E-2	55.6	60.9	.9
92281	92981	--	--	--	--	--	--	--	--	--	--	--	--	--
92981	100681	.62	.145	.220	.326	.51	1.57	.46	4.42	< .003	3.47E-2	126.5	130.4	1.0

NOTE - SULPHATE AS SO4; NITRATE AS NO3; AMMONIUM AS NH4; PHOSPHATE AS PO4

Fig. 6

Fig. 7

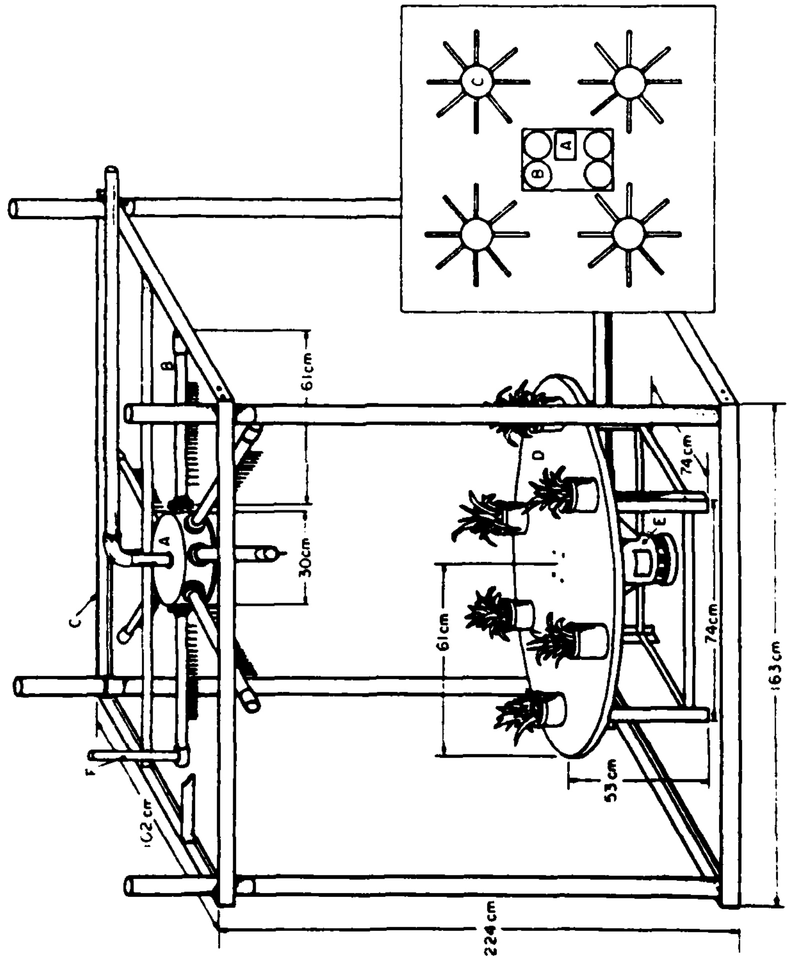
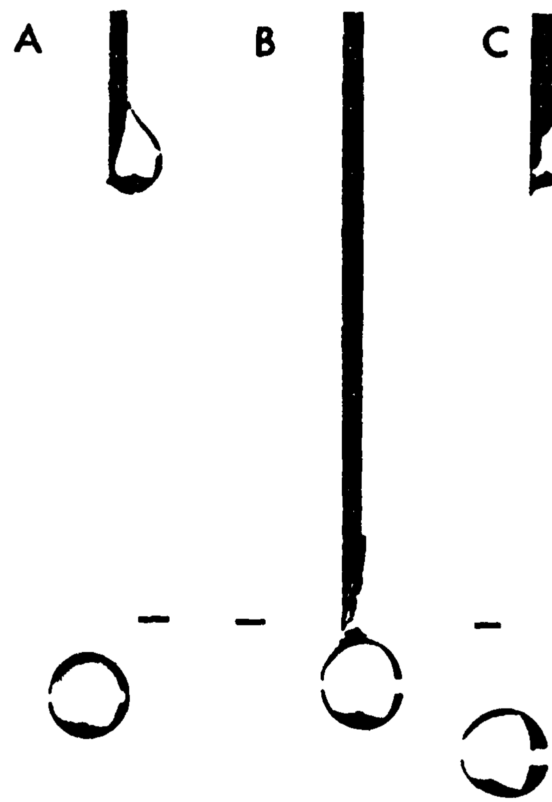


Fig. 8



F. LIST OF PUBLICATIONS

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Kress, L. W. 1977. Growth impact of O_3, NO_2 and SO_2 singly and in combination on two maternal lines of American sycamore. In Proc. Amer. Phytopath. Soc., Vol. 4.

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G. LIST OF SCIENTIFIC PERSONNEL

Dr. J. M. Skelly

Dr. B. I. Chevone

Dr. W. E. Winner

Dr. L. D. Moore

Dr. H. E. Burkhardt

Dr. Y. S. Yang (completed Ph.D. degree)

Dr. L. W. Kress (completed Ph.D. degree)

Mr. W. O. Phillips (completed M.S. degree)

Mr. L. L. Stone (completed M.S. degree)

Mr. C. R. Nicholson (completed M.S. degree)

RAINFALL CHEMISTRY AND POTENTIAL BENEFICIAL/DETRIMENTAL IMPACT TO INDIGENOUS VEGETATION

DAT

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